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Sea level variability in the Arctic Ocean from AOMIP models

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[1] Monthly sea levels from five Arctic Ocean Model Intercomparison Project (AOMIP) models are analyzed and validated against observations in the Arctic Ocean. The AOMIP models are able to simulate variability of sea level reasonably well, but several improvements are needed to reduce model errors. It is suggested that the models will improve if their domains have a minimum depth less than 10 m. It is also recommended to take into account forcing associated with atmospheric loading, fast ice, and volume water fluxes representing Bering Strait inflow and river runoff. Several aspects of sea level variability in the Arctic Ocean are investigated based on updated observed sea level time series. The observed rate of sea level rise corrected for the glacial isostatic adjustment at 9 stations in the Kara, Laptev, and East Siberian seas for 1954–2006 is estimated as 0.250 cm/yr. There is a well pronounced decadal variability in the observed sea level time series. The 5-year running mean sea level signal correlates well with the annual Arctic Oscillation (AO) index and the sea level atmospheric pressure (SLP) at coastal stations and the North Pole. For 1954–2000 all model results reflect this correlation very well, indicating that the long-term model forcing and model reaction to the forcing are correct. Consistent with the influences of AO-driven processes, the sea level in the Arctic Ocean dropped significantly after 1990 and increased after the circulation regime changed from cyclonic to anticyclonic in 1997. In contrast, from 2000 to 2006 the sea level rose despite the stabilization of the AO index at its lowest values after 2000.

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1. Introduction

[2] The ability of models to represent seasonal and interannual variability of sea surface height (SSH) is an important indicator of model validity because sea level (SL) or SSH reflects changes in practically all dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin. Approximately 70 tide-gauge stations in the Barents and Siberian Seas (Kara, Laptev, East Siberian, and Chukchi Seas) have recorded SL changes from the 1950s through the 2000s (Table 1 and Figure 1 in *Proshutinsky et al.* [2004]). These data are available for model validation at the Permanent Service for Mean Sea Level archive (http://www.pol.ac.uk/psmsl/pub/nucat.dat) and at the Woods Hole Oceanographic Institution web site (http://www.whoi.edu/science/PO/arcticsealevel).

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[3] Figure 1 shows the longest SL time series from 9 coastal stations in the Siberian Seas (see Figure 2 and Table 1 for station locations). There is a positive SL trend along the Arctic coastlines. For 1954–1989 the rate of SL rise for these stations was estimated as 0.194 cm/yr [*Proshutinsky et al.*, 2004]. Adding 1990–2006 data increases the estimated rate for these stations to 0.25 cm/yr. The SL time series correlates relatively well with the annual AO index (source: NOAA National Weather Service Climate Prediction Center http://www.cpc.noaa.gov), SLP at the North Pole (source: NCAR/NCEP reanalysis product) and SLP at the coastal stations mentioned above. Consistent with the influences of AO-driven processes, the SL dropped significantly after 1990 and increased after the circulation regime changed from cyclonic to anticyclonic in 1997 (*Proshutinsky and Johnson* [1997], updated).

[4] In contrast, from 2000 to 2006 the SL increased in spite of steady low AO index. Because of the large interannual variability, it is difficult to evaluate the significance of this change, but an analysis of model results can provide some insight into these recently observed changes. Of course, this is only possible if the model results agree well with the observational data. The major purpose of this study is to validate AOMIP models against SL observations by determining their major differences and causes for those differences. A second goal of this paper is to recommend model improvements by introducing neglected effects and mechanisms important for SL variability.

6. Conclusions and Recommendations

[52] In general, AOMIP ocean models with a free surface are able to simulate variability of SSH reasonably well but several improvements are needed to decrease model errors. Here we do not discuss any issues associated with model forcing fields and parameters, accuracy of numerical approximations, or parameterizations of internal ice and ocean processes. Some of these are discussed in other publications presented in this AOMIP special section. We focus on recommendations relatively inexpensive to implement (without significant changes in model codes) and possibly useful at least from the perspective of more complete model physics.

[53] 1. The first issue is model resolution, specifically the resolution of ocean bathymetry. It is found that in order to reproduce variability of SSH at the locations of tide gauges in the shallow Arctic seas, it is important to have a minimum depth of no more than 10 m. This change would allow models to more correctly reproduce SL variability associated with wind forcing and atmospheric loading (extreme magnitudes and phases of long waves or storm surges), propagation of waves resulting from river runoff (especially in June–July when river discharges reach their maximum and SL rises dramatically in river deltas), and formation of anomalies in water temperature and salinity fields, coastal circulations and sea ice regimes. Increasing the models' vertical resolution, recommended for instance by *Zhang and Steele* [2007], would improve simulations of Arctic halocline and processes of heat exchange between Arctic waters and the atmosphere and between surface Arctic waters and deeper layers.

[54] 2. We also recommend that models take into account forcing associated with atmospheric loading (IBE). This effect is responsible for SL variability not only at synoptic timescales (for example, storms) but also changes in SL at seasonal, interannual and long-term timescales. This is especially important for the Arctic Ocean which is separated from the rest of the World Ocean by relatively narrow or shallow straits that modify long wave propagation to the Arctic Ocean from the North Atlantic and Pacific Oceans. Studies by *Yoshida and Hirose* [2006] demonstrate that inclusion of the Arctic Ocean in a global ocean barotropic model affects the northwestern Atlantic Ocean through the propagation of Kelvin waves. Air pressure induces sea surface variability stronger than that forced by surface wind for most of the global oceans except the Southern Ocean. In the Arctic Ocean, the pressure induced component is responsible for more than 90% of the variability forced both by pressure and wind according to this publication. The water mass oscillates through the strait between the Arctic Ocean and the North Atlantic Ocean with a period of 10 days and an amplitude of about 8.5 Sv. Average SL lags because the basin- wide isostatic adjustment is only established by limited water exchange through the strait. Our 2-D regional model results confirm these conclusions (Figure 17).

[55] Inclusion of atmospheric loading in the oceanic model module must be accompanied by an atmospheric loading effect in the sea ice dynamics model module, to avoid artificial sea ice motion.

[56] Short period variability of ocean dynamics due to the IBE could be comparable with the effects of tidal forcing discussed by *Proshutinsky* [1993], *Kowalik and Proshutinsky* [1994], *Heil and Hibler* [2002], and *Holloway and Proshutinsky* [2007].

[57] 3. Our experiments with the 2-D barotropic model investigated the dynamical effects of fast ice. In these experiments, the fast-ice extent influences SL dynamics mechanically, primarily by damping the magnitude of long waves propagating under fast ice (storm surges, tides). These effects are important for the shallow Siberian seas and we recommend inclusion of fast ice in 3-D model simulations. The potential for upwelling and downwelling at ice boundaries was noted by *Gammelsrod et al.* [1975] using a homogeneous ocean model with stationary ice. *Clarke* [1978] and *Niebauer* [1982] extended these results to include stratification and meltwater, respectively. *Carmack and Chapman* [2003] concluded that the efficiency of shelf/basin exchange is strongly moderated by the location of the ice edge relative to underlying topography. Baroclinic effects are also important along the fast ice edge and we recommend investigating them with several AOMIP models. The implementation or parameterization of fast ice in 3-D models is an interesting and difficult task but it could be solved step by step, first implementing the relatively primitive empirical approach employed in our 2-D model simulations, then developing a model of fast ice formation and decay.

[58] 4. Bering Strait inflow and river runoff are important for the dynamics and thermodynamics of both sea ice and the ocean via their influence on freshwater and heat balances. We speculate and demonstrate that the pressure gradient associated with the Bering Strait inflow should drive the entire circulation of the Beaufort Gyre from the surface to bottom layers cyclonically with a speed of 1–2 cm/s and can be responsible for one of the mechanisms influencing redistribution of the Pacific waters in the Canada Basin. Almost all AOMIP models (except the NPS model version and the Alfred Wegener Institute model not discussed here) include Bering Strait and riverine influences, but this subject has not been investigated thoroughly in the scientific literature and more studies are needed.

[59] 5. Observations from 9 tide gauge stations representing SL conditions in the Siberian seas (Kara, Laptev, and East Siberian) show that SL is rising in this region at a rate of 0.25 cm/yr for the 1954–2006 period. There is also a well pronounced decadal variability in the observed SL time series that correlates with the AO [*Proshutinsky et al.*, 2004]. In agreement with AO behavior, the SL dropped significantly after 1990 but started rising again in 2002. This fact was confirmed by *Scharroo et al.* [2006] based on satellite observations over the entire Arctic Ocean. The SL time series obtained from this study revealed a negative SSH trend of −0.217 cm/yr (region from 60°N to 82°N) for the period 1995 to 2003. This is consistent with Figure 1. In contrast, the coastal data shows that from 2000 to 2006 the SL rise rate has increased despite a steady, low AO index. Because of the large interannual variability, it is difficult to evaluate the significance of this change. We anticipated that AOMIP model results would allow us to explain the recently observed SL variability, but significant differences among model results enable us only to speculate that the central Arctic SL drop registered by satellites could be associated with steric effects.